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Manufactured Home Testing in Simulated and Naturally Occurring High Winds

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Summary

A typical double-wide manufactured home was tested in simulated and naturally occurring high winds to understand structural behavior and improve performance during severe windstorms. Seven (7) lateral load tests were conducted at a remote field test site in Wyoming and then the home was exposed to high winds during the 2002 – 2003 winter. These tests were designed primarily to collect data necessary to investigate the transfer of wind loads across the marriage line and to calibrate a desktop analysis and design software tool under development at the Idaho National Laboratory (INL). An extensive instrumentation package monitored the overall behavior of the home and collected data. The results of this research can enable the advancement of building code requirements and be used to validate engineering software capable of predicting and optimizing wind resistance.

1. Introduction

The INL has conducted research designed to increase industry understanding of structural behavior and improve durability, windstorm resistance, and energy efficiency of manufactured homes. The 1998–2005 tasks included full-scale simulated lateral load tests on single- and double-wide homes, component testing of selected elements, field exposure of the homes to naturally occurring high winds, wind tunnel tests using scaled models, simulation of structural behavior, and prototype development of desktop engineering software validated using the test data.

This paper focuses on lateral load tests and natural wind performance of a USA Wind Zone 1 double-wide manufactured home at a field test site near Arlington, Wyoming (Refs. 1-2). The purpose of these tests was to determine the load-deformation relationships for the home at loads up to the approximate design lateral load (about 1676 Pa) and to specifically address load transfer across the marriage line. This information can be used in the development and validation of analytical computer models. U.S. Department of Housing and Urban Development (HUD), the Manufactured Housing Institute (MHI), and the U.S. Department of Energy (DOE) sponsored this research.

2. Test Design

For these tests, an 8.1 m x 18.3 m (26 ft 8-in x 60 ft) Kit Manufacturing Co. (Kit) 3 bedroom, 2 bath double-wide home was purchased. The home was structurally complete with ducting, insulation, plumbing, electrical system, roofing, siding, interior walls, etc. but without interior trim and most appliances. The materials and construction methods of this test home are representative of many homes currently produced by the manufactured housing industry.

The test home was transported to the test site by commercial carrier and installed using standard techniques (piers, tie-down straps) recommended by Kit (Ref. 3). The installation system was designed to be as typical as possible while not allowing significant displacement of the ground anchors or stretching of the tie-down straps during testing. Since the data is used to evaluate the structural response of the house, displacement in the foundation and tie-down system was undesirable. The typical tie-down straps were replaced with a system consisting of a hook over the I-beam frame member of the home, a turnbuckle to allow equalizing tension, a load cell, and Kevlar rope (high strength, less than 1% stretch, and non-conductive reducing lightning damage to instrumentation). The tie-down straps were attached to anchors embedded in either concrete piers or compacted soil.

The data acquisition (DAQ) hardware consisted of an IOtech DaqBoard 2000 system (Ref. 4, 16-bit, 200-kHz multi-channel A/D unit) and five IOtech 16-channel analog-input modules. The system was controlled using LabVIEW software (Ref. 5) on a PC. For each test, up to 125 channels of data were recorded as functions of time (2-5 samples/sec) including the applied loads (produced by airbag pressure, jack load, wind pressure), wind velocity and direction, tension in the tie-down straps, load transfer across the marriage line, global displacements measured with respect to a fixed reference frame, internal shear wall racking (extension or contraction of wall diagonals), shear displacement along the marriage line, and interface slip between, for example, walls and floors.

2.1. Simulated Lateral Loads

A strong wall system (structural steel, plywood surface, concrete piers) used previously by the research team to test a single-wide home in 1998 (Refs. 6-9) was modified and installed at a remote field test site near Arlington, WY (Figure 1). The home was placed with the western longitudinal outside wall approximately 76 mm (3-in) east of the strong wall with a continuous airbag filling the gap. Rigid wood posts along the opposite (east) outside wall of the home were installed providing a

Figure 1. Double-wide test home simulated lateral load tests

reference attachment and measurement for the global displacement transducers. After initial setup and instrument checkout, seven full-scale simulated lateral load tests were performed on the home. Loads consisting of either airbag uniform lateral pressure or a concentrated load near the roof line were applied slowly to reduce the dynamic response. Test durations were approximately 15 to 45 minutes with data continuously recorded at five (5) samples per second. The maximum airbag pressure was 1676 Pa (35 psf). The maximum concentrated load was 14.86 kN (3340 lbf). Figure 2 shows the location of the applied loads.

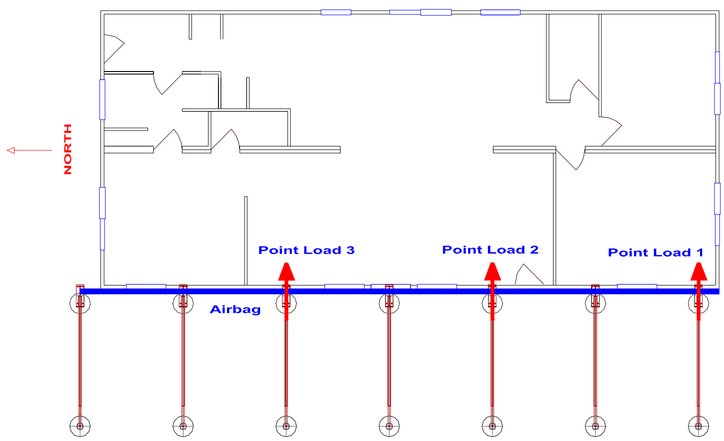

Figure 2. Location of applied airbag and point loads

The marriage line (Figures 3 and 4) was instrumented with 48 load cells and five (5) displacement transducers (LVDTs) to measure force transfer and shear displacement between the two sections of the home. These load cells (4.5 kN or 1000 lbf range in both tension and compression) were installed at locations where the Kit installation manual (Ref. 3) required the use of 9.5 mm dia. x 152.4 mm length (3/8-in x 6-in) lag bolts.

Figure 3. Installation of marriage line load cells on floors, exterior walls, ceiling, and roof

In other locations where actual lag bolts were installed, spacer blocks of 152.4 mm x 152.4 mm x 12.7 mm thick (6-in x 6-in x ½-in) OSB were used to maintain a 12.7 mm (½-in) gap (same thickness as load cell brackets). The only structural contacts between the two marriage line surfaces were at the two types of interfaces; lag bolts with spacer blocks or load cell/bracket systems. The air spaces in the gap were filled with lightweight, non-structural insulation to minimize air ingress/egress.

2.2 Naturally Occurring Winds

Following the lateral load tests, the reaction wall was removed and the home was exposed to naturally occurring high winds during Oct. 2002 – May 2003. In addition to the instrumentation in place for the previous tests, a 64-channel pressure scanner system measured dynamic wind pressures on the outside walls and roof.

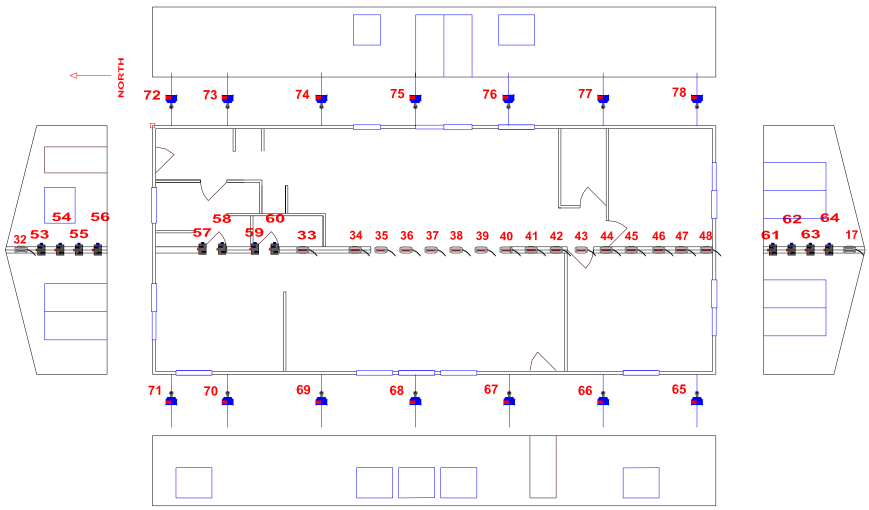

Figure 4. Plan view showing location of marriage line and tie-down load cells (14 ceiling and 4 roof load cells not shown)

A 10 meter meteorological tower was installed next to the home with three RM Young vane-prop anemometers (located at the elevations of the eve, 6.7 m, and 10 m, relative to the ground) to measure wind speed and direction. Other meteorological data including temperature, humidity, and barometric pressure were also collected. Data was collected at a rate of two (2) samples/sec.

3. Results

3.1 Simulated Lateral Load Tests

Detailed analyses of these data are reported in Ref. 10. The data generally show near-linear initial system response with significant non-linear behavior as the applied loads increase. Load transfer across the marriage line is primarily compression (Figures 5 and 6). For example, load cell 43 in Figure 5 is initially set at +520 N (+117 lbf) by tightening the attachment bolts creating tension in the load cell and compression in the marriage line. As the airbag pressure is increased, the differential load (measured load – initial set) decreases to about –609 N (–137 lbf) indicating increased compression across the marriage line.

Global vertical displacements are all $\leq$ 1.5 mm (0.06-in) indicating that the tie-down straps and foundation piers are as rigid as designed, i.e., stretch in the tie-downs and settling in the piers were minimal. Horizontal global displacements away from the reaction wall reached approximately 15.2 mm (0.6-in). A comparison of the ceiling versus floor global horizontal displacements indicates that the home moved almost directly away from the applied load without significant rocking.

Racking, while present, is $\leq$ 0.76 mm (0.03-in). Interface slip and shear displacement along the marriage line are nearly insignificant ($\leq$ 0.15 mm or 0.006-in).

3.2 Naturally Occurring Lateral Load Tests

While we were unable to capture an extreme wind event, several events with sustained strong winds were recorded. One such event is presented here, along with a brief discussion of the home response. On March 2, 2003, between 7:00am and 7:00pm, the minimum 1 sec lull was 7.5 m/s (16.8 mph), the 1-sec peak gust was 31.3 m/s (70.1 mph) and the 12-hr mean wind speed was 18.9 m/s (42.3 mph). A time history of the wind speed at the 10-meter elevation anemometer is shown in Figure 7.

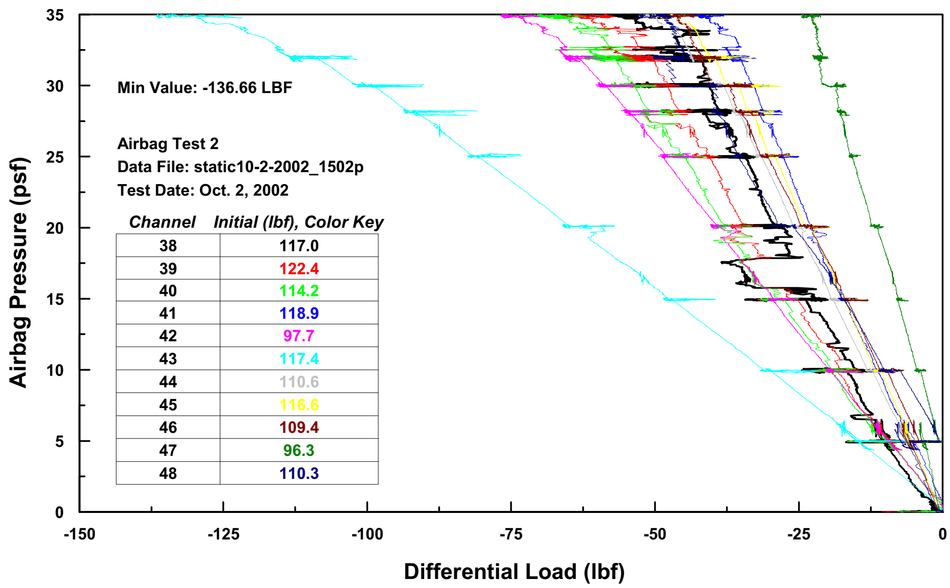

Figure 5. Force Transfer Across South Floor Marriage Line versus Airbag Pressure

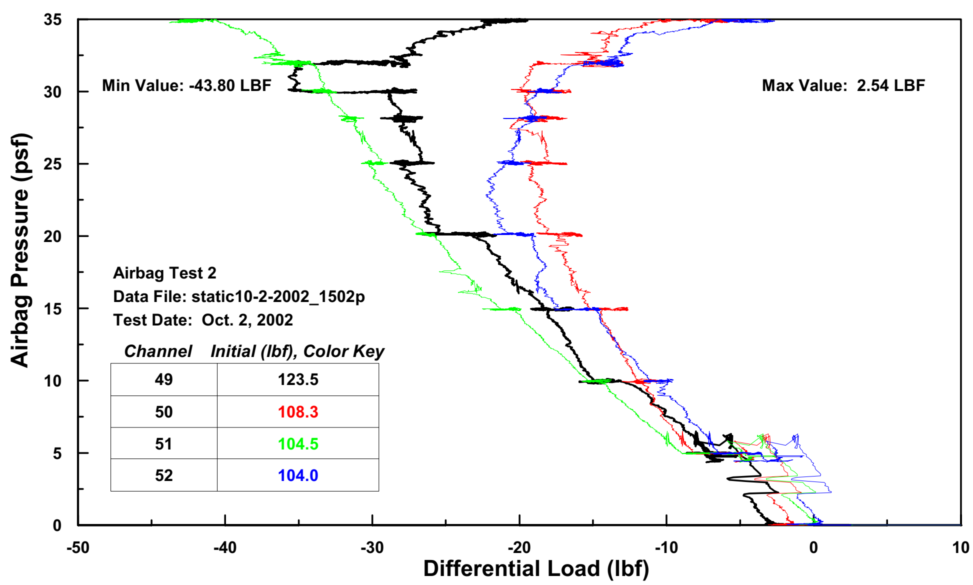

Figure 6. Force Transfer Across Roof Marriage Line versus Airbag Pressure

In order to look at the response of the home, a 10-minute slice beginning at 1:10 pm was evaluated at the full temporal resolution recorded (0.5 sec sample rate). The location of this data slice is shown by two vertical bars on the 12-hour wind trace in Figure 7. Figure 8 is trace of the wind speed and direction over the 10 minutes of interest. The mean speed was 22.1 m/s (49.4 mph) from a bearing of 239°. The peak ½-second gust was 30.0 m/s (67.1 mph) and the peak 3-second gust was 28.3 m/s (63.3 mph). Given the 11.3° bearing of the home centerline, the wind impinged on the longitudinal walls 42.3° from perpendicular, striking the west (long) wall and south (end) wall with nearly equal intensity. Average wind pressures on the roof and windward wall during this event are shown in Figures 9 and 10.

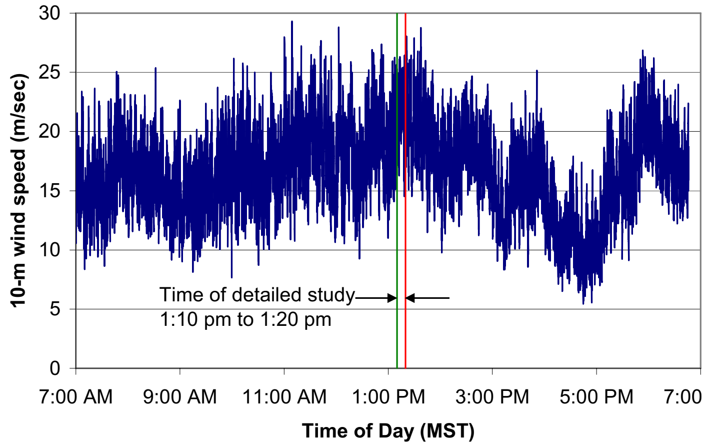

Figure 7. 12-hour 10-meter wind speed record, March 2, 2003

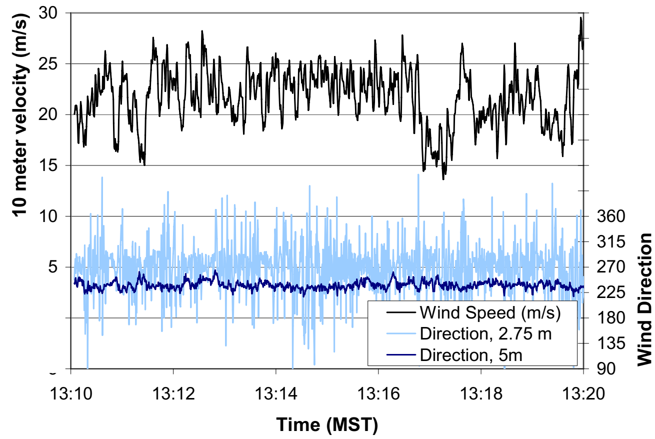

Figure 8. 10-minute traces of wind speed and direction at 0.5 sec resolution

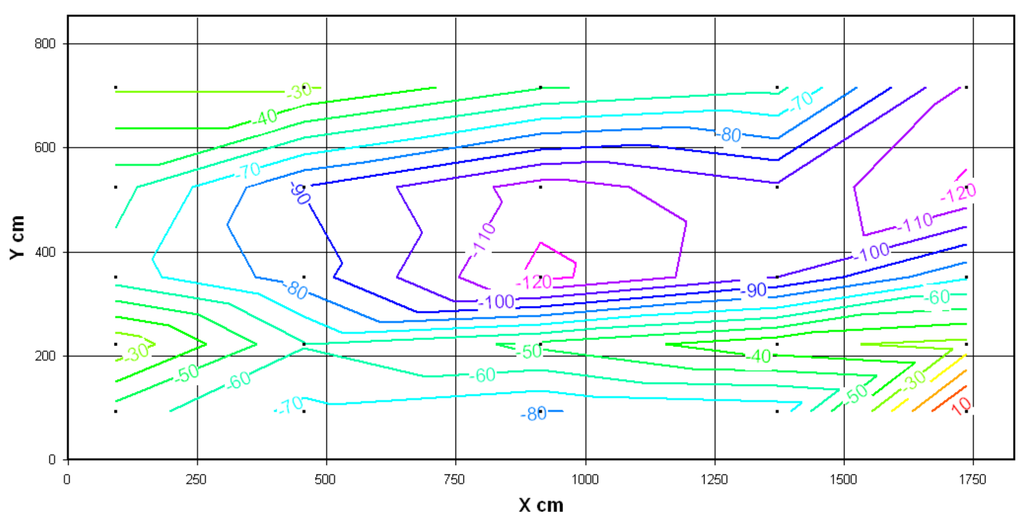

Figure 9. 10-minute average pressure distribution on the roof (Pascal)
View looking down on roof, north is to the left. Pressure taps shown as dots.

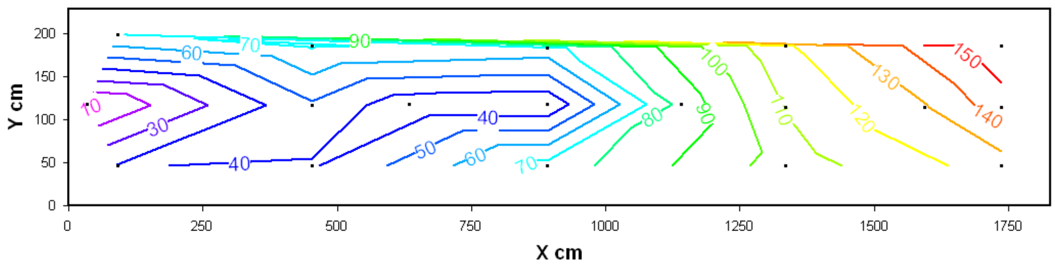

Figure 10. 10-minute average pressure distribution on the west (long) wall (Pascal). View from home exterior looking east. Pressure taps shown as dots.

Figure 11 presents data traces from a few representative load cells with a wind speed trace for visual correlation by the reader. The upper trace is the wind speed, with its ordinate axis to the right. The middle two traces are tie-down forces at the upwind corner mid wall span (load cells 65 and 68, as shown in Figure 4). The larger of the two is the corner tie-down. As can be seen, tie-down loads track nearly instantaneously with wind speed. This would suggest that tie-down anchors be sized for the absolute peak gust.

The lower two traces in Figure 11 represent the tension in connectors at the marriage line on the roof. The higher trace is load cell 50, 20 feet from the south end, and the other is load cell 49, at the south end. Bolt tension at these locations is slightly reduced during strong gusts, but the effect is negligible, showing that the marriage line is not activated at this wind speed. Other load cell data taken along the marriage line at the ceiling and floor levels (not shown here) are less responsive to rapid changes in wind velocity than load cells at the roof line.

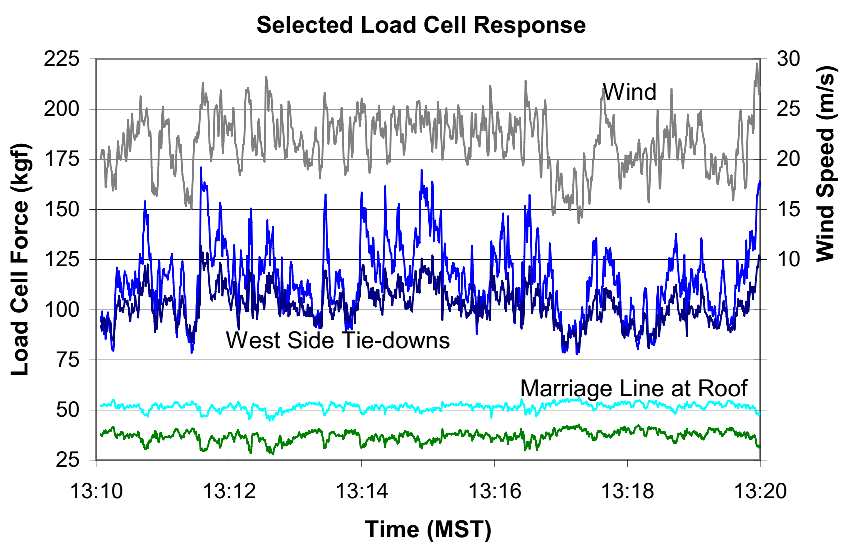

Figure 11. 10-minute traces of wind speed and direction at 0.5 sec resolution

4. Conclusions

A wealth of structural performance and wind pressure data was collected during our tests on a typical double-wide manufactured home. These data could be used to validate analysis software, design tie-down systems using actual loading, and to evaluate existing methods of attaching sections at the marriage line. The data generally show near-linear initial system response with significant non-linear behavior as the applied loads increase. Load transfer across the marriage line is primarily compression. Racking, while present, is very small. Interface slip and shear displacement along the marriage line are nearly insignificant. Horizontal global displacements during the simulated lateral load tests reached 15.2 mm (0.6 inch) . Our test data indicate that transfer of wind load into the tie-down straps is immediate, following the absolute peak gust. Forces across the marriage line follow the applied lateral load but are much less responsive to rapid changes in wind velocity than the tie-down straps.

Even though the global, marriage line shear, interface, and racking displacements are small, the double-wide home lateral load test data coupled with data from separate effects experiments (primarily shear wall tests, Ref. 11) are a valuable addition to the data base of performance information available for use in analysis tool validation. The INL has worked on prototype analysis software (MH Tool, Ref. 12) that could be completed and used to predict the structural behavior of a variety of manufactured housing designs to high winds.

5. References

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